Subsoil caves characterization by means of the interpretation of electrical resistivity tomography. Application to Clunia and Atapuerca archaeological sites

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ABSTRACT: The aim of this research is to develop a suitable methodology for the interpretation of Electrical Resistivity Tomography (ERT) images from the subsoil (obtained with direct-current), specifically applied to the detection of caves, holes and the structural characterization of a karstified limestone formations related to archaeological sites.

The location and characterization of holes and caves by means of the geophysical technique is nowadays being resolved in various several ways, because there is not a clear and safe method for the resistivity profile interpretation. This work compiles a novel series of tests performed on well-known objectives that analyse the effects of the main factors that condition resistivity images.

This work has two different practical parts: 1.- Laboratory test: Electrical response tests performed on well-known objectives. 2.- Field work: ERT applied to prospect the endokarst morphologies and the sedimentary infills of two archaeological sites in Burgos (Spain), the roman city called Colonia Clunia Sulpicia and the Pleistocene archaeo-palaeoanthropological sites of Atapuerca.

The operations needed to obtain subsoil images by using Electrical Resistivity Tomography are relatively simple; however their after interpretation is very complex. By performing controlled tests it has be identified the areas that offer a specific electrical response according to several different sub-soil models and to the multielectrodical device used.

1 INTRODUCTION

Recent years, there has been a significant increase in Geoelectrical prospecting applied in geophysical investigation to hydrological studies, mining and geotechnical research (Dahlin, 2001; Griffiths and Barker, 1993; Daily and Ramirez, 2000M, Maillol *et al*, 1999), as well as in environmental studies and in archaeology (Griffiths and Barker, 1994; Piro *et al*, 2000 and 2001; Chambers *et al*, 2002; Astin *et al*, 2007; Drahor, M. G. *et al*, 2008; Cardarelli and Di Filippo, 2009; Papadopoulos *et al*, 2006 and 2010; Tsokas *et al*,. 2009), proving its utility as non destructive technique for subsurface exploration.

The application of Electrical Resistivity Tomography (ERT) for imaging of subsurface discontinuities and lithological contacts is well documented (Beresnev *et al,* 2002). ERT constitutes an important advance in the geoelectric methods because it solves automatically the manual change of electrodes, characteristic of the classic geoelectrical methods (Vertical Electrical Sounding). In this way, ERT facilitates the management and fast processing of a large number of data, constituting a useful non-destructive method to detect subsurface structures.

2 DESCRIPTION OF THE ERT METHOD APPLIED TO CAVES DETECTION

Electrical tomography is a geoelectrical surveying method that analyzes subsoil materials according to their electrical impedance, which, in other words, allows them to be differentiated according to their resistivity (Aracil, E. et al., 2002 and 2003). Factors that condition the presence of a greater or lesser concentration of ions depend on the nature and composition of the rocks, and their texture that may be more or less altered, or compact, or porous, in relation to their fluid content and their nature.

Greater mobility of these ions has as a consequence, greater conductivity, or conversely less resistivity, which is the parameter used in electrical resistivity tomography (Orellana, 1982).

The resistivity or conductivity of the water, as the greater the conductivity of the water, the lower the resistivity of the rock formation in which it is found (Sumanovac, F.; Weisser, M., 2001).

According to Heiland's (1940) amplified equation, the resistivity in the rock will depend fundamentally on four factors:

$$\rho = \frac{F}{v} \cdot \rho_w \cdot \frac{1}{F_s}$$

in which, ρ is the resistivity of the rock, F is the formation factor, v is the porosity factor, ρ_W the resistivity of the water contained in the rock or soil, and F_S the saturation factor. The porosity factor is defined as the proportion in volume of cavities in the rock. It takes values between 0.08-0.15 for sand, sandstone, porous limestone and compact clays. This definition of v coincides with that of porosity n, for which reason reference will henceforth be made to n. The formation factor depends on the form and distribution of the pores. The rocks that are most affected by factor F are sandstones, quartzites, limestones and shales.

Electrical Resistivity Tomography (ERT) data for this study were collected by measuring 2D Dipole-Dipole and Wenner-Schlumberg ERT profiles with different electrode arrays determined by the location and the depth under study. The electrical imaging surveys were carried out with a SYSCAL R1+ SWITCH 72 resistivity meter.

The results of this type of geophysical surveying are the electrical tomography profiles (see figure 1) that are simply vertical sections of the ground that are colour coded with the different resistivity measurements. The colour coding is shown in a legend at the bottom of each profile.

Consequently, once the geo-electrical prospecting research using ERT is underway different resistivity values will be determined and attributed to materials that will permit identification of lithological units of differing natures, lithologies with different textures or degrees of deterioration, structural (fractures) and geomorphologic aspects (caves and infills) etc (Porres, 2003).

Data acquisition requires the positioning of an array of electrodes along a transversal section, each separated at a particular distance according to the required degree of resolution (less spacing between electrodes, greater resolution) and depth of the investigation (greater spacing between electrodes, greater depth).

Each one of these resistivity data measure, is attributed to a particular geometric point in the subsurface. The electrical images are, in fact, cross-sections of land that reflect the distribution of resistivity values at different depths corresponding to the different layers of investigation (Loke, 2000).

The depth of the investigation, therefore, will depend on the spacing between electrodes and the selected layout may easily run deeper than 100m in depth, even though shallower test boreholes into the subsurface have the definite advantages of greater resolution, as there is generally less separation between electrodes. As a rule, the resolution of the investigation decreases logarithmically in relation to the depth (Dahlin y Loke, 1998).

Figure 1 shows a device made up of 36 electrodes, each spaced at 3 m intervals, capable of creating an image of a longitudinal section of 105 m and 16 m of investigation depth.

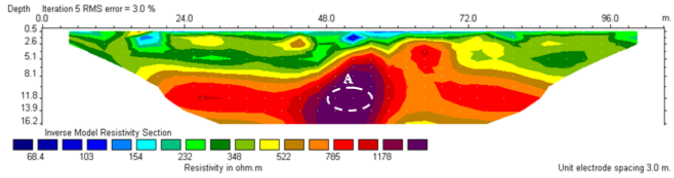

Figure 1. ERT profile 2D. Shows a positive anomaly (A) corresponding unfilled cavity karstified limestone (Clunia archaeological site, Spain)

3 LABORATORY TESTS ON A SMALL SCALE: ELECTRICAL RESPONSE OF KNOWN MODELS.

In order to meet the electrical response of different geological conditions, laboratory tests were carried out on small-scale models.

Figure 2 shows the data acquisition process for an air-filled big hole in a layer of sand, trying to simulate a geology similar to that shown in figure 1, showing an air-filled karst cavity in a full scale test.

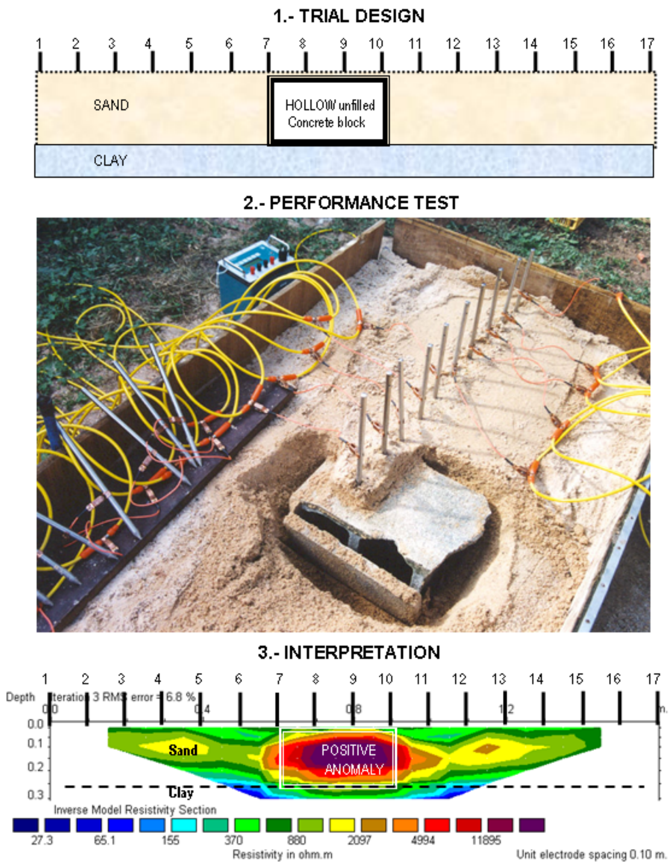

Figure 2. ERT laboratory test on a small scale and its corresponding result as a 2D profile image.2D (Porres J.A., 2003)

Multitude of test were conducted on a small scale, observing the influence of 5 variables in the 2D images obtained: 1- Electrode array (Schlumberger-

Wenner and Dipole-dipole), 2- Separation distance between electrodes, 3- Depth of investigation, 4- Size and shape of the holes investigated, 5- Kind of filling inside the cavities.

3), so we have based the geophysical interpretation mainly on the Schlumberger-Wenner array data. In addition, the sections were drawn without vertical exaggeration, in order to facilitate georeferencing and projection of the karstic passage topography. The topography of the geophysical sections was elaborated from topographic surveys.

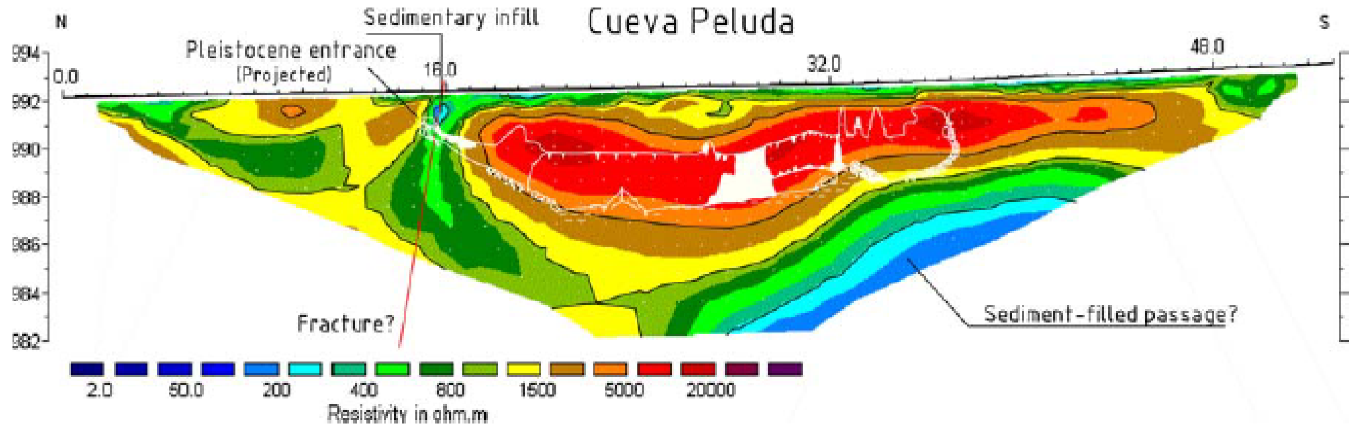

Figure 3. ERT profile recorded over "Cueva Peluda" karstic passage in Atapuerca, The whiteline shows the internal wall of the cave (Ortega et al 2010)

The results showed the best choice of electrode array and electrode spacing, depending on the size, depth, shape and fill of the hole to locate.

field work: ERT applied to prospect the endokarst morphologies and the sedimentary infills of two archaeological sites in Burgos (Spain)

Electrical Resistivity Tomography profiles were taken to identify the characteristics of the subsoil as geophysical method for the specific objective of identifying different types of infill, localize possible subsoil cavities and identify the fractures that affect the limestone massif in which the Atapuerca and Clunia caves are located (Zhou, W. et al., 2000).

The application of appropriate geophysical surveying methods to each objective provides knowledge of the subsoil materials and their layout to a greater or lesser degree of precision. Concretely, this geophysical survey method well used will allow the materials at different depths to be studied at different degrees of resolution (Martínez-Pagán, et al., 2005).

The field work sections were carried out with the resistivity device SYSCAL R1 PLUS Switch72, and were processed using the software RES2DINV ver.3.42 (Locke, 1999). In every section, we applied Schlumberger-Wenner and Dipole-Dipole electrode arrays. Most of the profiles present similar results using the Dipole-Dipole and Schlumberger-Wenner arrays, although in a few profiles they differ substantially, specially in those where the prospection depth is increased (Athanasiou *et al*, 2007).

In theses cases, the Dipole-Dipole showed the highest root-mean-squared errors. Also the Schlumberger-Wenner profiles provide more realistic images according to the endokarstic and geological structures observed in the Cueva Peluda control profile (Figure

3.1 *Pleistocene archaeo-palaeoanthropological sites of Atapuerca, Burgos, Spain.*

The geophysical interpretation of these sections was supported by archaeological and geological field observations, 1:50.000 and 1:10.000 geological and geomorphological surface maps (Pineda, 1997; Benito, 2004), and using the geomorphology of the known endokarst system, elaborated by detailed surveying (Ortega, 2009).

In the same way, section represented on Figure 3 was carried out along the abandoned rail cutting above the well-known shallow main passage of the Peluda Cave and was used as a first control for the resistivity response of the cavities, sediments and materials. In this section, the Dipole-Dipole and Schlumberger-Wenner arrays show similar results. Figure 3 presents a closed structure denoted by the highest resistivity values (> 1500 ohmm, corresponding to the empty cavity of Cueva Peluda, barely a few meters (1-2 m) under the current floor of the railway cutting, between 992 and 990 m asl.

This structure is surrounded by rock (Upper Cretaceous carbonates), defined by a wide range of resistivities (> 400 ohmm), according to its fracturation degree, local facies and stratification. In the profile, a third zone with the lowest resistivity values (< 400 ohmm) can be distinguished.

The latter correspond to non-consolidated and higher porosity material, which correspond to a sediment-filled old entrance and passage, such as was observed in several sections carried out in the site.

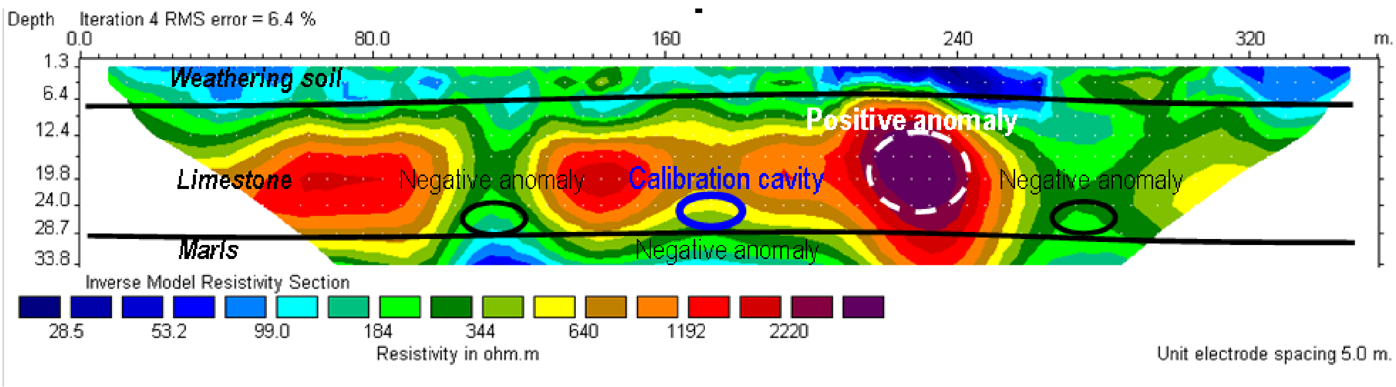

Figure 4. ERT profile recorded over a karstic passage in Colonia Clunia Sulpicia. The blueline shows a calibration cavity which shape, fill and depth was well known, and the whiteline shows an positive anomaly who shows the internal wall of a big cave under the Roman Baths area (Porres, 2003).

3.2 *The roman city called Colonia Clunia Sulpicia Site, Burgos, Spain.*

The geology of Clunia and surrounding areas is limestone outcrops that crown the upper Miocene tertiary series.

Micritic limestone is sometimes brecciated, whose thickness ranges from 5 to 15 meters.Under the limestone in the series is a section of marls interbedded with lenticular sand bodies that gradually give way to carbonate crusts where Miocene limestones occur as described above.

In this sense, it seems that the Roman city is located in a very favorable place for the development of karst aquifers on carbonate formations. These cavities are filled with archaeological remains, were occupied by the Romans for various rituals and its water content was used daily.

The morphology and layout of the cavities must have been highly conditioned by the presence of fractures which would have logically been the conduits through which the water passed, which caused the formation of these caves. An effort has been made to analyze these fractures using the same type of geophysical surveying but with the profiles located on the external surface of the limestone massif. These profiles, taken with different equipment to reach greater depths, identified certain anomalies which, on account of their morphology and their resistivity values, must be fractures in which the circulation of water and the depositation of fines would give them their characteristically low resistivity values in this type of geophysical profile (Negative anomaly at figure 4).

The calibration of Profile showed in Figure 4 was possible because we know the existence of a cave under our ERT profile. The dimensions of the calibration cavity is 10 m wide and 3 m high, and is located at a depth of 25 m. It is known that the cavity is partially filled with water, so their behaviour is likely to be conductive.

The profile has 5 m as electrode spacing, so it shows 355 m lengh and 33,8 m depth.

There is a clear high resistivity anomaly (>2200ohm.m, whiteline in figure 4) that seems clear evidence resistive gap on the right side of the profiles, distance 230. Is an anomaly that significantly distorts the normal values in the limestone itself is located, which could be around 650 ohm.m.

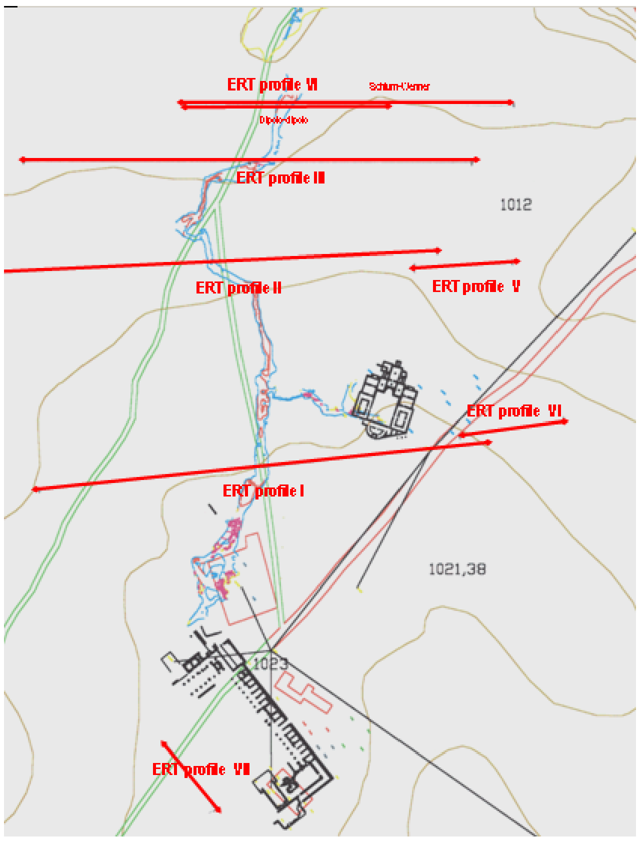

Figure 5. Diagram of the ERT profile distribution. The 2D profile of Figure 4 is located in the ERT profile I (Porres J.A., 2003)

4 CONCLUSIONS

Is essential to select the most suitable multielectrodical configuration that must be used on each case to locate holes and buried structures.

It has been shown a unique experience which proves that by means of a proper interpretation of electrical resistivity profiles, it can be accurately detect, the depth, size, shape and filler of surface holes or bigger underground caves specifically applied to archaeological sites.

Electrical Resistivity Tomography (ERT) has been a useful non-destructive geophysical method for imaging the subsurface structures of the Sierra de Atapuerca and Clunia sites, as well as its endokarst system, whose entrances were occupied by Early and Middle Pleistocene hominids in the first case, and by Roman occupation 2000 years ago in the second.

The use of detailed geomorphological and geological maps of the endokarst system and the surface landscape was essential to reduce the uncertainty of the geophysical interpretation. High resolution ERT prospecting made it possible to detect and analyze structures related to the site formation and distribution, such us bedrock morphologies, cavities continuity, geometries and thickness of sedimentary infills, and old entrances filled by sediments.

Deeper prospecting, related to longer length and lower resolution sections, was suitable to analyze deeper geological structures which controlled the development of the endokarst.

The analysis of this information contributes important new data about the configuration and geodynamic evolution of the endokarst. The geophysical prospecting thus allowed us to infer the connection, between allegedly isolated cavity systems in Atapuerca and Clunia endokarst. This work is fundamental for the understanding of the distribution of archaeological sites in the area and to plan their future research.

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6 REFERENCES

Aracil, E. (2002): La tomografía eléctrica como técnica versátil aplicable a la obra civil. En: IV Jornadas de Geotecnia. Vías de Comunicación. Burgos, 9th - 10th May, 2002. Servicio Publicaciones Escuela Politécnica Superior de Universidad de Burgos.

Aracil, E.; Maruri, U.; Porres, J.A.; Espinosa, A.B. (2002): "La tomografía eléctrica: una herramienta al servicio de la obra pública". *Rock Máquina*, 76 (30-34).

Aracil, E.; Maruri, U.; Vallés, J.; Martínez Pagán, P.; Porres, J.A. (2003): "Evaluación de problemas medioambientales mediante tomografía eléctrica". *Ingeopress*, 122 (34-39).

Aracil, E. (2009): "El Geólogo Geofísico". En: La profesión de Geólogo (Barrera, J.L., Ed.). ICOG (Madrid).

Arsuaga, J. L., Martínez, I., Gracia, A., Carretero, J. M. and Carbonell, E. (1993): Three new human skulls from the Sima de los Huesos site in Sierra de Atapuerca, Spain. *Nature* 362: 534-537.

Arsuaga, J. L., Martínez, I., Gracia, A., Carretero, J. M., Lorenzo, C., García, N. and Ortega, A. I. (1997). Sima de los Huesos (Sierra de Atapuerca, Spain). The site. *Journal of Human Evolution* 33(2/3): 109-127.

Astin, T., Eckardt, H. and Hay, S. (2007). Resistivity Imaging Survey of the Roman Barrows at Bartlow, Cambridgeshire, UK. *Archeological Prospection* 14: 24-37.

Athanasiou, E. N., Tsourlos, P. I., Papazachos, C. B. and Tsokas, G. N. (2007). Combined weighted inversion of electrical resistivity data arising from different array types. *Journal of Applied Geophysics* 62: 124-140

Benech, Ch. and Hesse, A. (2007): Some Considerations on the Integration of Geophysical Data into Archaeological Research. In *Geophysik aund Ausgrabung. Einsatz und Auswertung zerstörungsfreier Porspektion in der Archäoloie, Internationale Archäologie Naturwissenshafrt und Technologie* (Ed): 175-186.

Benito, A. (2004): *Análisis geomorfológico y reconstrucción de paleopaisajes neógenos y cuaternarios en la Sierra de Atapuerca y el valle medio del río Arlanzón*. PhD Tesis, Universidad Complutense, Madrid, Spain, 381 pp, ISBN 84-669-2585-6.

Benito-Calvo, A., Pérez-González, A. and Parés, J. P. (2008). Quantitative reconstruction of late Cenozoic landscapes: a case study in the Sierra de Atapuerca (Burgos, Spain). *Earth Surface Processes and Landforms* 33: 196-208.

Beresnev, I. A.; Hruby, C. and Davis, C. (2002). Exploration Geophysics. *Journal of Applied Geophysics* 49: 245-254.

Cardarelli, E. and Di Filippo, G. (2009). Integrated geophysical methods for the characterisation of an archaeological site (Massenzio Basilica – Roman forum, Rome, Italy). *Journal of Applied Geophysics* 68: 508-521.

Chambers, J. E., Ogilvy, R. D., Kuras, O., Cripps, J.C. and Meldrum, P. L. (2002). 3D electrical imaging of know targets a controlled environmental test site. *Environmental Geology* 41: 690-704.

Dahlin, T. (2001). The development of DC resistivity imaging techniques. *Computer and Geosciences* 27: 1019-1029.

Dahlin, T., Loke, M.H. (1998): Resolution of 2D Wenner resistivity imaging as assessed by numerical modelling. Journal of Applied Geophysics, 38. pp. 249

Daily, W. and Ramirez, A. L. (2000). Electrical imaging of engineered hydraulic barriers. *Geophysics* 65: 83-94.

Drahor, M. G., Berge, M. A., Kurtulmus, T. Ö., Hartmann, M. and Speidel, M. A., (2008). Magnetic and Electrical Resistivity Tomography Investigations in a Roman Legionary Camp

Site (Legio IV Scythica) in Zeugma, Southeastern Anatolia, Turkey. *Archaeological Prospection* 15: 159-186.

Flint, R.C., Jackson, P.D., McCann, D.M. (1999): Geophysical imaging inside masonry structures. NDT&E International, 32. pp. 469-479

Ford, D. C. (1977). Genetic classification of solutional cave systems. *Proc. Of the 7th International Congress of Speleology*, Sheffield. 189-192.

Gautam, P.; Paj Pant, S.; Ando, H. (2000) Mapping of subsurface karst structure with gamma ray and electrical resistivity profiles: a case atudy from Pokhara valley, central Nepal. Journal of Applied Geophysics, 45, 97-110.

Griffiths D.H.; Barker R.D. (1993) Two-dimensional resistivity imaging and modelling in areas of complex geology. Journal of Applied Geophysics, 29,211-226.

Griffiths, D. H., Turnbull, J. and Olayinka, A. I. (1990). Two-dimensional resistivity mapping with a computer-controlled array. *First Break* 8: 121-129.

Griffiths, D.H. and Barker, R.D. (1994). Electrical Imaging in Archaeology. *Journal of Archaeological Science* 21: 153-158.

Heiland, C.A. (1946) *Geophysical Exploration* Prentice Hall Inc New York 634.

Loke, M. H. (1999): *RES2DINV ver. 3.42, Geoelectrical Imaging 2D & 3D, User Manual*.

Loke, M. H. and Barker, R. D. (1996). Rapid least-squares inversion of apparent resistivity pseudosections using a quasi-Newton method. *Geophysical Prospecting* 44: 131-152.

Loke, M.H. (2000): Electrical imaging surveys for environmental and engineering studies. A practical guide to 2-D and 3-D surveys. University of Birmingham web site, Downloads:
www.bham.ac.uk/EarthSciences/people/staff/loke_m.html

Loke, M. H. and Dahlin, T. (2002). A comparison of the Gauss-Newton and Quasi-Newton methods in resistivity imaging inversion. *Journal of Applied Geophysics* 49: 149-162.

Maillol, J. M., Seguin, M.-K., Gupta, O. P., Akhauri, H. M., and Sen, N. (1999). Electrical resistivity tomography survey for delineating uncharted mine galleries in West Bengal, India. *Geophys Prospect* 47: 103-116.

Martínez Pagán, P.; Aracil, E.; Maruri, U.; Faz, Á. (2005): "Tomografía eléctrica 2D/3D sobre depósitos de estériles mineros". *Ingeopress*, 138 (34-36).

Orellana, E. 1982. Prospección Geoeléctrica en Corriente Continua. 2ª ed. Madrid. Paraninfo Vol.1.

Ortega, A. I. (2009). *Evolución geomorfológica del Karst de la Sierra de Atapuerca (Burgos) y su relación con los yacimientos pleistocenos que contiene*. Unpublished PhD Thesis, Universidad de Burgos, Burgos, Spain, 624 pp. I Annex Planimetric Documentation (11 maps, 12 long-sections, 91 cross-sections).

Ortega, A.I., Benito-Calvo, A., Porres, J., Pérez-González and Martin-Merino, M.A. (2010) Applying Electrical Resistivity Tomography to the Identification of Endokarstic Geometries in the Pleistocene Sites of the Sierra de Atapuerca (Burgos,Spain). *Archaeological Prospection, Published online in Wiley Online Library (wileyonlinelibrary.com) DOI: 10.1002/arp.*

Palmer, A. N. (1991). Origin and morphology of limestone caves. *Geological Society of America Bulletin* 103: 1-21.

Papadopoulos, N. G., Tsourlos, P., Tsokas, G. N. and Sarris, A. (2006). Two-dimensional and three-dimensional Electrical Imaging in Archaeological Site Investigation. *Archaeological Prospection* 13: 163-181.

Papadopoulos, N. G., Yi, M.-J., Kim, J.-H., Tsourlos, P. and Tsokas, G. N. (2010). Geophysical investigation of tumuli by means of surface 3D Electrical Resistivity Tomography. *Journal of Applied Geophysics* 70: 192-205.

Parés, J. M. and Pérez-González, A. (1995). Paleomagnetic age for hominid fossils at Atapuerca archaeological site, Spain. *Science* 269: 830-832.

Parés, J. M., Pérez-González, A., Rosas, A., Benito, A., Bermúdez de Castro, J. M., Carbonell, E. and Huguet, R. (2006). Matuyama-age lithic tools from the Sima del Elefante site, Atapuerca (northern Spain). *Journal of Human Evolution* 50: 163-169.

Pineda, A. (1997). Mapa Geológico de España escala 1:50.000, 2ª Serie (MAGNA). Hoja de Burgos, 200 (19-10). IGME, Madrid, 93 pp.

Piro, S., Mauriello, P. and Cammarano, F. (2000). Quantitative Integration of Geophysical Methods for Archaeological Prospection. *Archaeological Prospection* 7: 203-213.

Piro, S., Tsourlos, P. and Tsokas, G. N. (2001). Cavity detection employing advanced geophysical techniques: a case study. *European Journal of Environmental and Engineering Geophysics* 6: 3-31.

Porres, J. A. (2003). *Caracterización de cavidades en el subsuelo mediante la interpretación de perfiles de Tomografía Eléctrica*. PhD Thesis, Publisher: Universidad de Burgos, Burgos, Spain. ISBN:9788496394551. 343-346.

Tsokas, G. N., Tsourlos, P. I., Stampolidis, A., Katsonopoulou, D. and Soter, S. (2009): Tracing a Major Roman Road in the Area of Ancient Helike by Resistivity Tomography. *Archaeological Prospection* 16: 251-266.

Porres, J.A. (2003): "Caracterización de cavidades en el subsuelo mediante la interpretación de perfiles de Tomografía Eléctrica: Aplicación al yacimiento arqueológico de Clunia" Phd. Thesis ISBN 978-84-96394-55-1. 2007

Sumanovac, F.; Weisser, M. (2001) Evaluation of resistivity and seismic methods for hydrogeological mapping in karst terrains. Journal of Applied Geophysics, 47. 13-28

Zhou, W.; Beck, B.F.; Stephenson, J.B. (2000) Reliability of dipole-dipole electrical resistivity tomography for defining depth to bedrock in covered karst terranes. Environmental Geology, 39 (7), 760-766.